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Investigation of Equivalent Stator-Winding Thermal Resistance during Insulation System Ageing

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Abstract—High performance electrical machine operation is limited by the losses generated in the machine and how well the heat developed by these losses is extracted. For conductive heat transfer from the main winding body, the insulation materials provide the main heat transfer pathway. As a machine ages through its lifetime, these materials will change their properties, and therefore these heat transfer characteristics will also alter. This paper describes the methodology and measurements on a set of motorettes undergoing an insulation ageing process to identify the change in heat transfer characteristics. The motorettes are subjected to a combination of thermal, electrical, mechanical and humidity stresses, before their thermal performance is measured. It has been found that the equivalent thermal resistance of the motorettes over the nominal lifetime of the insulation increases by over 100%, with the current carrying capability of the machine reducing by over 30% across the machine's lifetime. It is therefore recommended that this is taken into account during the initial thermal design of the machine to ensure it remains fit for purpose during its complete life.

Keywords—Insulation ageing, heat transfer, motorette testing, insulation stress

I. INTRODUCTION

A continuous drive towards electrification of previously mechanically powered transmission systems is pushing electric machine performance towards increasingly demanding levels, for instance in high power or torque density, high efficiency, high speed, and high reliability. The key to machine high performance is effective management of its losses through the design of the machine and appropriate thermal management.

There are several power loss sources present in an electrical machine during its normal operation, categorised as either electromagnetic or mechanical [1]. The power losses manifest themselves in an elevated temperature, distributed across the machine body. If the losses are inadequately managed, this usually leads to thermal degradation of the machine performance and/or premature failure [2] [3]. In this context, the winding assembly is particularly challenging to design appropriately. The winding is frequently associated with the main heat source within the machine body, with the generated heat often difficult to extract in an effective manner [1]. The resultant dissipative heat transfer from the winding body to the machine periphery is governed by a number of fundamental heat transfer mechanisms including conduction, convection and radiation [4]. This work however, is focused on a class of

machines, where conduction is the main heat extraction mechanism from the winding into the core pack/machine periphery.

There are numerous factors affecting the conductive heat transfer across from the winding body. These include thermal properties of the constituent materials, e.g., winding wire, wire coating, varnish and slot liner, and the processes used in construction of the winding assembly. The manufacture and assembly processes are particularly difficult to quantify theoretically, and an empirical approach is preferred here providing a more reliable data [5]. In general, there are two factors, which have significant impact on the stator-winding conductive heat transfer: the equivalent thermal conductivity of composite winding material and contact thermal resistance between winding body and core pack/slot [6-9]. It is possible to derive and separate both of these quantities by the use of appropriate experimental testing and modelling techniques. However, when performing tests on a large number of hardware samples, as considered in this investigation, such an approach might be impractical. The measured equivalent stator-winding thermal resistance provides a mean of assessing the 'goodness' of the heat transfer path as the electrical insulation system ages during the accelerated aging procedure.

As previously mentioned, the insulation system of wound components or machine windings is often made from a number of elements, including; wire coating, slot liner and either varnish or alternative potting compound. During the life cycle of the winding, these materials age, degrading the properties of the insulation and ultimately leading to failure. There have been a number of studies attempting to model this anticipated insulation life, based on thermal [10] [11], electrical [12] and multi-stress scenarios [13-16]. Standards have developed to allow designers to understand the temperature constraints and life of materials [17] [18].

However, there has been little published research into how insulation ageing effects the thermal performance of a machine. As insulation ages, micro-cracks appear in the insulating material, creating small voids of air, reducing the insulation capacitance and resistance [19]. It is expected that as the electrical properties of the insulation system deteriorate, so will the thermal properties. This can lead to an increased degradation in the insulation system, as the increased temperature in the winding causes the insulation to degrade faster, worsening both electrical and thermal insulation properties, for the same operating conditions. In this scenario,

the life of the insulation system would degrade a lot faster than would normally be expected.

Here, an equivalent stator-winding thermal resistance, which combines both the material and manufacture /assembly factors, was used [20] [21]. The experimental approach used in this investigation allows for measurements of the equivalent stator-winding thermal resistance to be carried out in a repeatable and decoupled manner, i.e. other heat transfer effects present during the tests do not affect the measured data. The thermal resistance measurements are supplemented with the standard electrical insulation measurements to understand the state of insulation degradation.

This paper builds on the work published in [22], which presented the initial first two ageing cycles. The following work carries on from this initial paper, presenting the results after 10 ageing cycles on a batch of motorettes, of a representative high specific power output machine. Analysis is conducted on the results to understand the effect of this on machine design and performance towards the end of life.

II. EXPERIMENTAL METHODOLOGY

To achieve a statistically relevant sample, a batch of six motorettes has been manufactured to evaluate the change in thermal resistance between the winding body and stator as the insulation ages. The motorette is based on the design for a permanent magnet, high performance aerospace machine, which has an open slot, single layer winding in a modular configuration. Fig. 1 shows a photo (a) and cross-section (b) of the motorette.

The motorette base is made from solid mild steel. The coil is wound in a two-in-hand configuration from a compacted type-8 Litz wire, which has a polyester inner coating and polyamide imide overcoat, rated to class N (200°C). 3M Thermavolt slotliner is used, rated to class R (220°C), located between the coil and the motorette base and between the upper and lower levels of the coil. The complete assembly is then impregnated with Elantas ELAN-protect UP142 non-solvent based varnish, rated to class N (200°C). The motorette is instrumented with 8 thermocouples, in the following locations:

- 2 in mid-slot, between winding layers;
- 1 in each end winding, between winding layers;
- 1 in each side tooth of the motorette base;
- 1 on the centre tooth of the motorette base;
- 1 on the bottom of the motorette base.

The thermocouples in the winding are installed during the manual winding process, with those in the motorette base installed when required during the heat transfer testing.

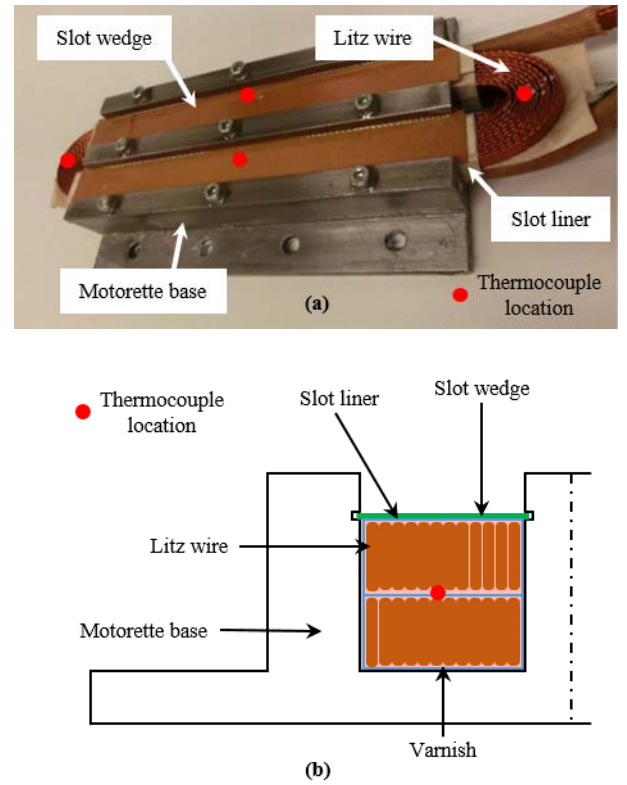


Fig. 1. Motorette used in insulation ageing tests (a) photo and (b) cross-section.

Following the procedure in IEC 60216 [18], the motorettes are conditioned at 200°C for 72 hours, before conducting the ageing procedures. One complete ageing cycle comprises four stresses applied to the motorettes sequentially, shown in Table I, before the heat transfer testing is conducted, which evaluates the equivalent thermal resistance. Each cycle represents approximately 10% of insulation life.

After each stress is applied to the motorette, the electrical properties of the insulation, impedance and resistance, are measured to assess the impact of the stress on the insulation performance. The insulation is assumed to have failed when the insulation resistance has reduced by a factor of 10^6 from the initial measurements.

TABLE I. AGEING STRESSES APPLIED TO MOTORETTES.

Stress	Description	Time
Thermal	Heat at 240°C	168 hours
Electrical	600V square wave @ 10 kHz	1 hour
Vibration	1.5 g, 50 Hz (1.5 mm) @ 30°C	1 hour
Humidity	85% RH, 30°C	48 hours

III. EXPERIMENTAL SET-UP

The ageing cycles take place in a number of different facilities. The thermal conditioning and stressing takes place in a forced air Carbolite oven, in a dedicated oven laboratory, shown in Fig. 2 (a), with all six motorette samples aged concurrently. A Keysight B2985A High Resistance Meter is used to apply the electrical stress to the motorette insulation, Fig. 2 (b). The vibrational stress is applied through the motorette base by using a Data Physics V350 shaker, driven by the Data Physics SignalStar vibration controller, one motorette at a time. The shaker head is located inside a TAS Environmental Chamber, to maintain a constant temperature during the test vibration stressing, Fig 2 (c). A Votsch VC7034 Climatic Chamber is used to apply the humidity stress to the motorettes, which is shown in Fig. 2 (d).

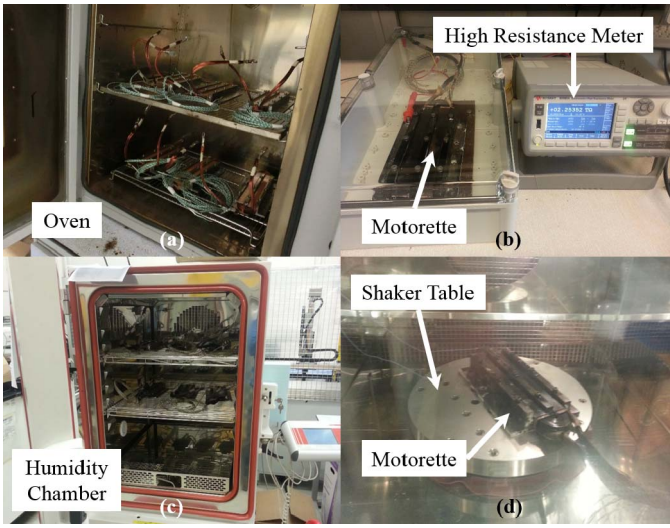


Fig. 2. Insulation ageing equipment used to apply stresses to motorettes. (a) Applying thermal stress in oven, (b) Keysight High Resistance Meter applying 600V electrical stress, (c) Humidity stressing motorettes in climatic chamber, and (d) vibrating motorette on a shaker table.

The insulation capacitance, dissipation factor and resistance are measured after each stress application. The insulation capacitance and dissipation factor are measured with a Wayne Kerr Precision Analyser 6500B, Fig. 3 (a), at frequencies between 20 Hz and 120 MHz, with the values of capacitance and dissipation factor extracted at 100 Hz, 1 kHz, 10 kHz and 100 kHz. The insulation resistance is measured using the Keysight B2985A High Resistance Meter, Fig. 2 (b), at a DC voltage of 600V applied across the insulation over a period of 10 minutes, with the insulation resistance recorded at 1, 5 and 10 minutes.

The equivalent thermal resistance is measured using the equipment shown in Fig. 3 (b). The instrumented motorette is attached to a liquid cooled cold-plate, connected to a chiller unit, which maintains the temperature of the liquid at 15°C. This is placed within a thermally insulated chamber, to enable the only heat extraction to take place through the cold-plate. The coil is connected to a DC power supply, and current is passed through the coil to generate a loss within the coil, and therefore an increased temperature. The system is left to reach a steady state, which is defined as less than 1°C change in

temperature over 10 minutes. At this point, the system is said to have reached thermal equilibrium, where the input power to the coil is equal to the output power extracted by the cold-plate. The power and temperature profile is recorded at the equilibrium point. This is carried out at four different points, and a chart can be drawn of the input power against the temperature rise between the winding and the back of the motorette base, as shown in Fig. 4; the equivalent thermal resistance is then the gradient of this chart. The lower the value of equivalent thermal resistance, i.e. the shallower the gradient on the graph, the better the system is at extracting heat from the winding body. (In Fig. 4, system 1 has better heat extraction performance than system 2, as the gradient is shallower.)

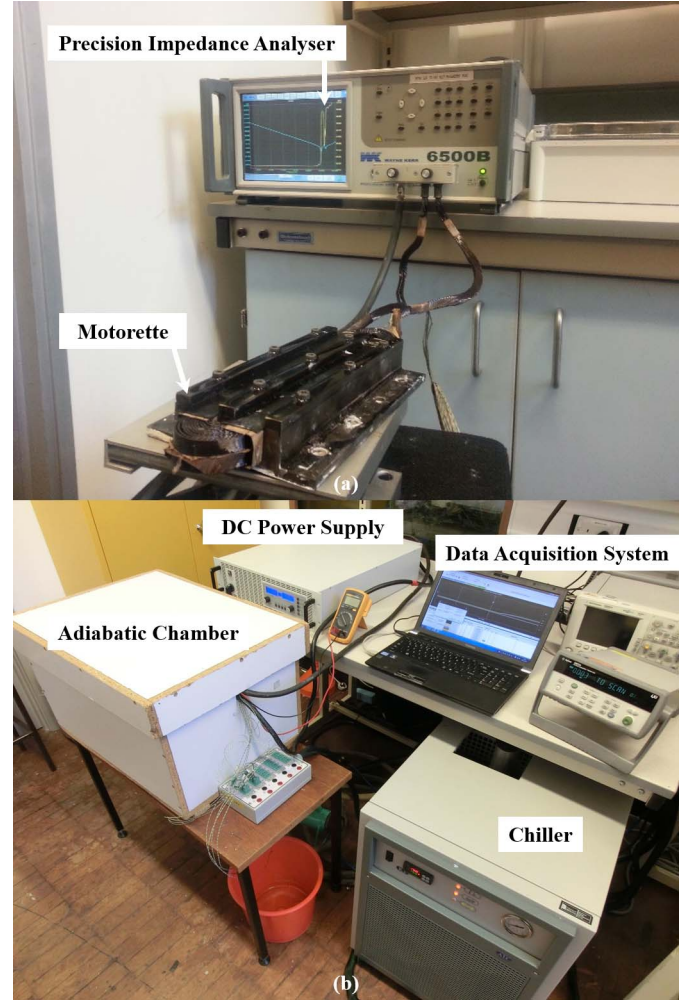


Fig. 3. Measurement equipment used to measure insulation properties after stressing motorettes. (a) Measuring motorette insulation impedance on Wayne Kerr Precision Impedance Analyser, (b) Test set-up to evaluate equivalent thermal resistance between the winding body and stator.

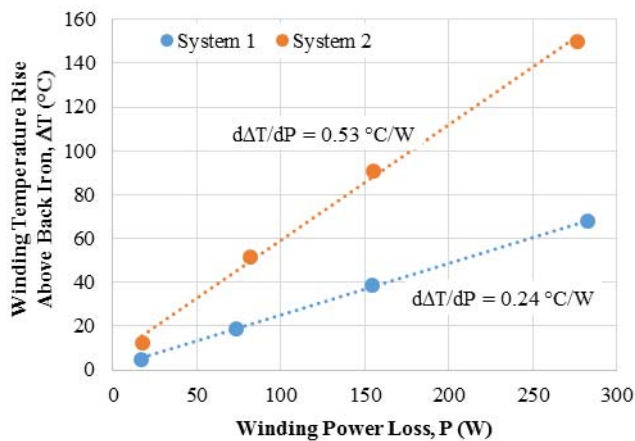


Fig. 4. Evaluating equivalent thermal resistance ($d\Delta T/dP$) from heat transfer tests.

The calculated values of equivalent thermal resistance can then be used in an equivalent thermal network model of a machine to improve the thermal performance modelling. This resistance can also be altered over the lifetime of the machine, to reflect the changes determined in the experimental investigation, allowing an understanding on how the insulation ageing will affect the machine performance as the machine ages.

IV. RESULTS AND DISCUSSION

Initial conditioning and 10 ageing cycles have been completed at the time of writing. This is approximately equivalent to the life of the machine, or 20 000 hours of operation. The measured insulation capacitance, dissipation factor and insulation resistance for each motorette at each stage are shown in Fig. 5. The two preliminary measurements were done after varnish impregnation and thermal conditioning. These were then followed by the 10 cycles of the sequential stress applications as described in Section II.

As can be seen in Fig. 5, the insulation resistance has slowly decreased over the series of stressing cycles, with a marked decrease in insulation resistance in the 9th and 10th cycles. When the motorettes go through a humidity cycle there is a large decrease in insulation resistance, which is to be expected as the moisture causes a lower resistance path between the winding and motorette base. As the motorette dries out, the insulation resistance increases again. During the

humidity testing in cycle 10, the insulation resistance of motorette 1 reduced to less than 1 MΩ, and therefore failed the test. All the other motorettes are currently still serviceable.

Fig. 6 shows the insulation capacitance also decreasing as the insulation ages, with peaks of capacitance during the humidity stressing cycle. Similarly, the dissipation factor has increased, Fig. 7 with peaks for the humidity stressing cycle. As can be seen in both of these figures, the failed motorette does not appear to show on either of these charts. This could be due to the low voltage applied to record these measurements, compared to the high voltage applied for the insulation measurements.

The change in equivalent thermal resistance over time is shown in Fig. 8. It appears that this is initially linear, with the later results appearing to plateau. The increase in equivalent thermal resistance is marked, with the average increasing from 0.23°C/W to 0.49°C/W, or 113% increase.

This increase in equivalent thermal resistance will have repercussions on the performance of the machine, as the ability to extract heat (power) from the winding body has decreased by over 100% at nominal full life. Assuming that power dissipation ability is proportional to the square root of the current, the per unit current carrying capability of the machine therefore decreases to the square-root of the ratio of the current to initial equivalent thermal resistance; this is plotted in Fig. 9. This figure shows that there is a reduction of 31% in the per unit current as the machine approaches the end of its life, suggesting therefore that there is an equal 31% reduction in torque carrying capacity during its lifetime.

These results suggest that there is significant variance in the thermal performance of machine between first construction and end-of-life. Therefore, the end of life performance needs to be assessed during the initial design stages of the machine, to ensure that it is able to perform as required over the complete life. This will mean oversizing the machine for its initial performance to allow enough performance degradation to achieve the desired torque capacity at the end of life. An alternative to oversizing the machine is to specify the insulation materials to a higher temperature class, e.g. class R instead of class N, which would likely reduce the effect of any temperature related degradation. Often in the thermal design of a machine the initial machine thermal properties are used, however it is recommended that aged thermal properties are used instead as these provide a more conservative and realistic value for operating properties.

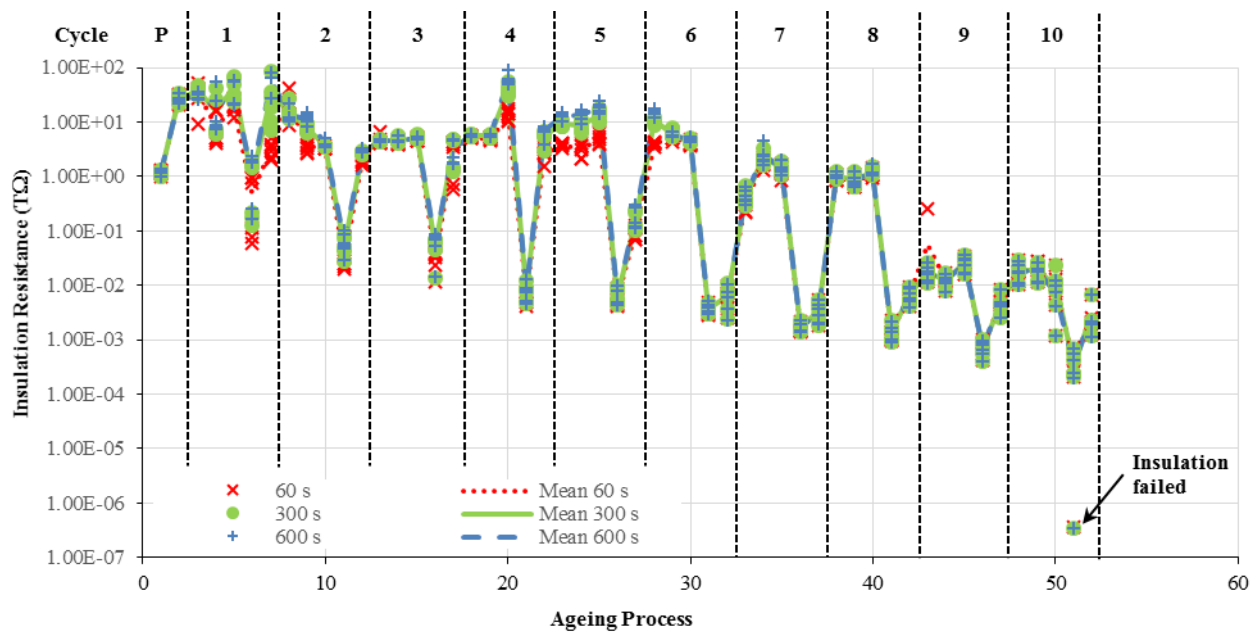


Fig. 5. Insulation resistance over insulations ageing cycles 1 – 10.

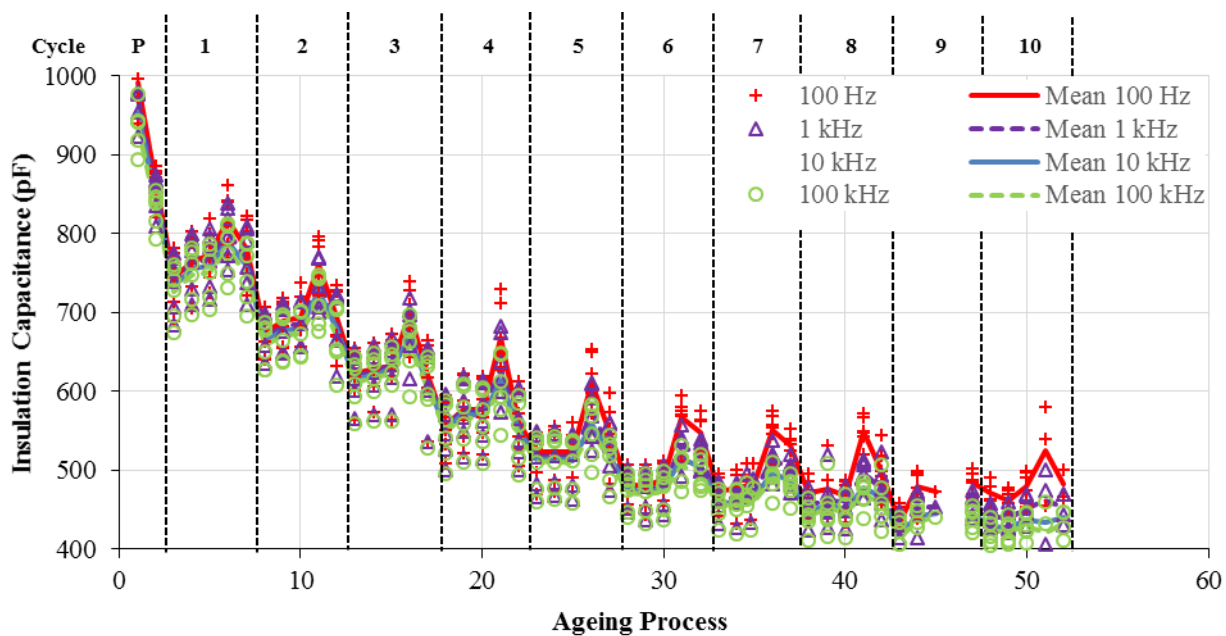


Fig. 6. Insulation capacitance over insulations ageing cycles 1 – 10.

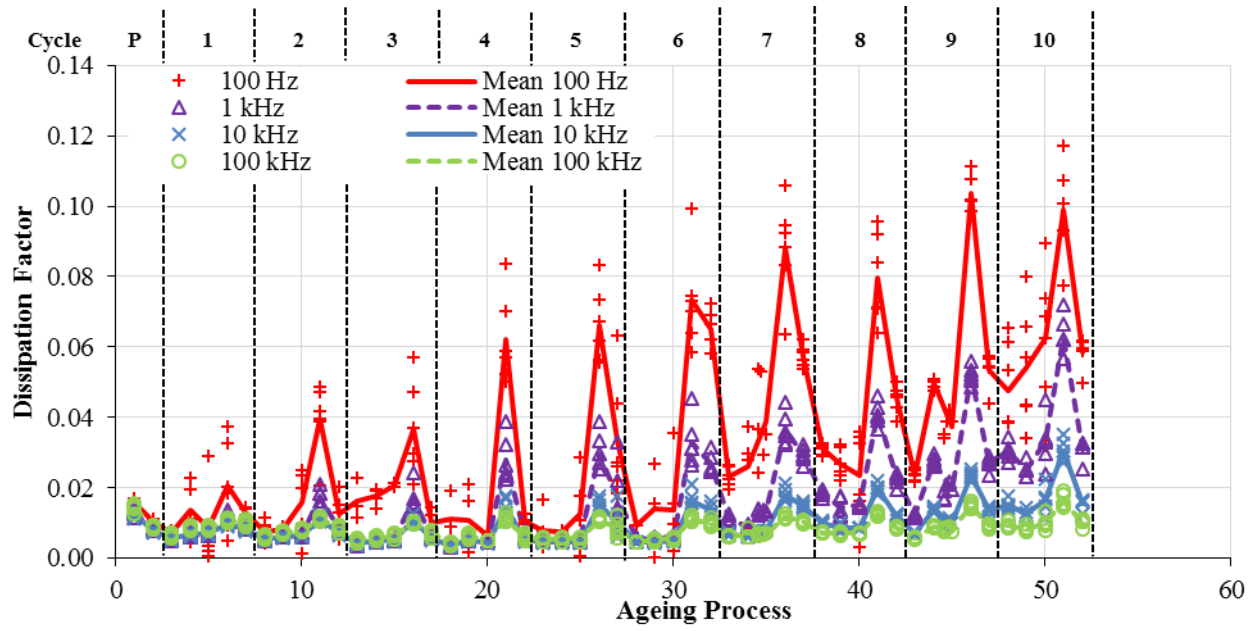


Fig. 7. Insulation dissipation factor over insulations ageing cycles 1 – 10.

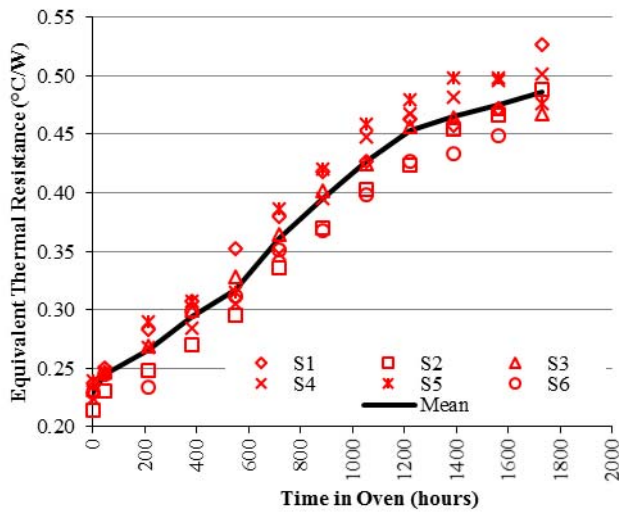


Fig. 8. Heat transfer coefficient change as insulation ages.

The results in Figs 5-8 show reasonable consistency between all the samples, with each sample following similar trends as the motorette ages, therefore we can be confident that the results are representative for this motorette design and material selection.

The results suggest that the hypothesis of electrical insulation and thermal conduction properties simultaneously degrading appears to be valid. The microcracks generated from the insulation ageing processes create a more convoluted path to extract the heat, increasing the equivalent thermal resistance. The results in Fig. 8 suggest that the increase in equivalent thermal resistance becomes less severe towards the end of life, which implies that the major changes within the insulation take place in the initial stressing cycles.

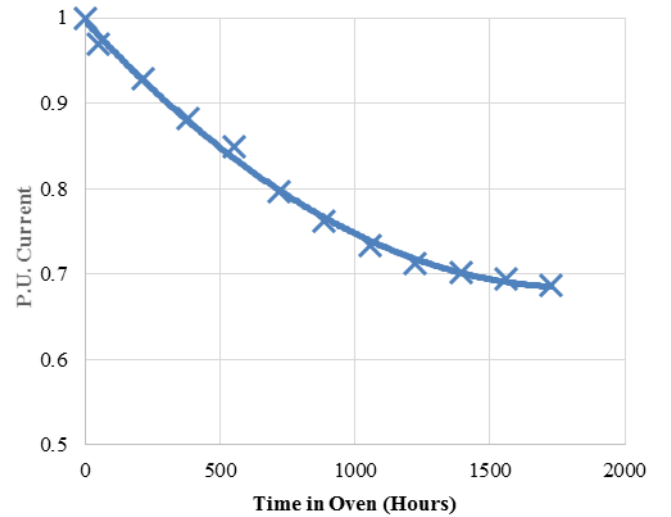


Fig. 9. Per unit current change as insulation ages.

V. CONCLUSIONS

This paper has described the experimental derivation of the equivalent thermal resistance for a motorette, and how it changes as the insulation ages. It has been shown that for the motorette used, the equivalent thermal resistance increases by over 100% over the nominal insulation life. This results in a reduction in torque carrying capability of the machine as it ages of 30%, which will restrict the performance of the machine and cause the machine to not achieve the desired output within safe thermal limits.

Further work should be carried out on additional motorettes to verify these findings, and an attempt to identify the dominant effect from the degradation – either the material thermal

conductivity or the contact thermal resistance between the winding body and stator. This would be achieved through further testing of a number of different insulation system combinations. From this, an empirical model can be developed to determine this change, so it can be calculated without having to conduct the insulation ageing tests. If these heat transfer tests were included in standard ageing testing procedures, then a large amount of data would be able to be produced to evaluate these effects further.

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